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TIP VORTEX CAVITATION DELAY WITH APPLICATION TO MARINE LIFTING --ETC(U)
AUG 79 G P PLATZER, W G SOUDERS

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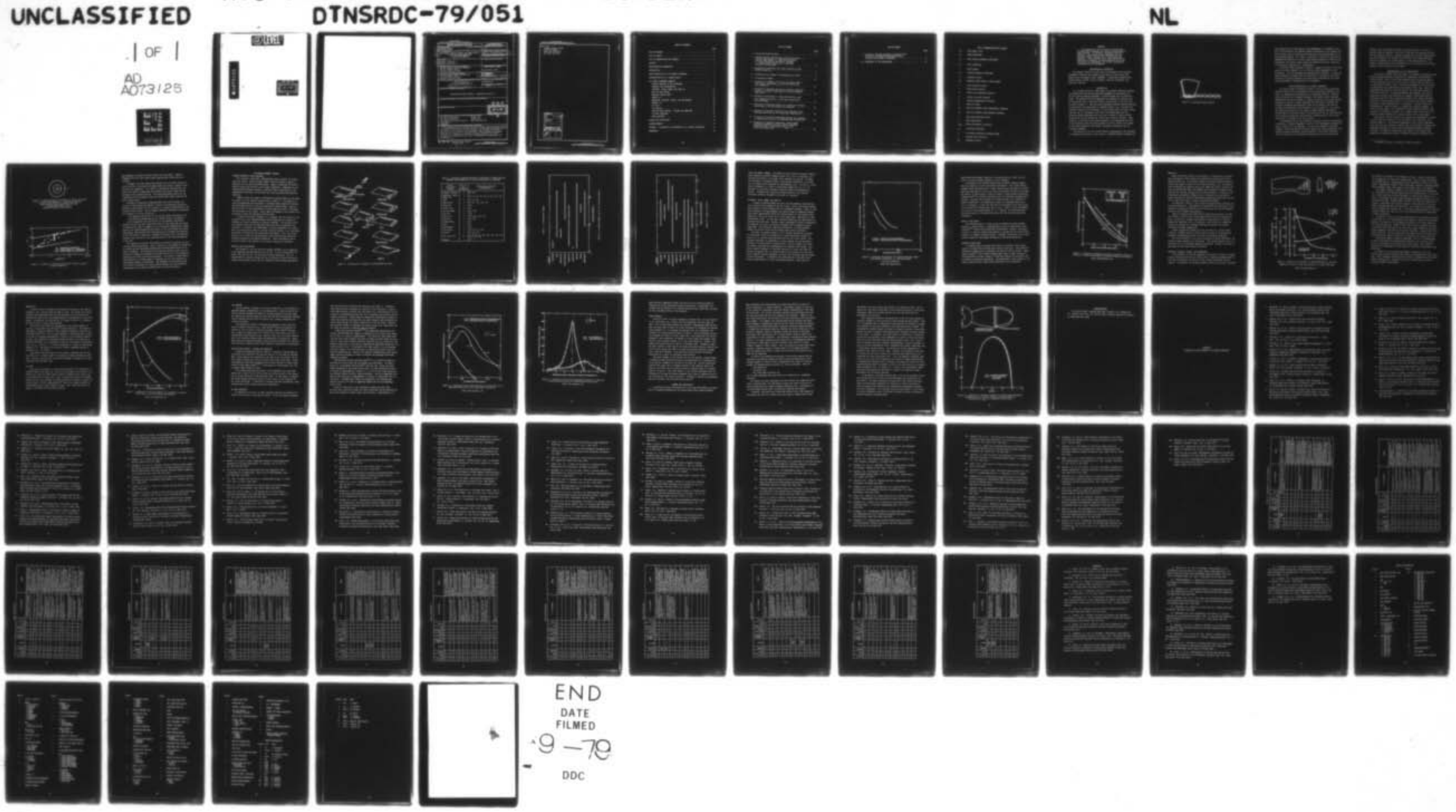

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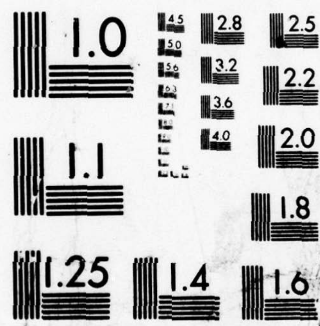


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The generation of tip vortices from finite-span lifting surfaces degrades the overall effectiveness of these surfaces. An extensive literature survey pertaining to this viscous rollup phenomenon and the numerous concepts advanced for its alleviation has been made. Those concepts which appear applicable to delaying the formation of marine propeller tip vortex cavitation are highlighted, and further experimental investigations are recommended.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AR | Wing aspect ratio |
| $C_D$ | Drag coefficient |
| $C_j$ | Mass ejection momentum coefficient |
| $C_L$ | Lift coefficient |
| c | Chord length |
| $J_A$ | Propeller advance coefficient |
| R | Propeller radius |
| $R_n$ | Reynolds number based on chord length |
| r | Local propeller radius |
| U | Free-stream velocity |
| $V_i$ | Vortex core tangential velocity |
| w | Vortex core axial velocity |
| z | Distance downstream of wing tip |
| $\alpha$ | Angle of attack |
| $\delta_1$ | Wing tip boundary layer displacement thickness |
| $\delta_2$ | Wing tip boundary layer momentum thickness |
| $\varepsilon$ | Wing span efficiency factor |
| $\Gamma$ | Wing circulation |
| $\Gamma_{max}$ | Wing circulation at mid span |
| $\eta_0$ | Propeller efficiency |
| $\sigma$ | Tip vortex cavitation inception index |
| $\Omega$ | Average local vorticity |
| $\Omega_0$ | Maximum vorticity |

## ABSTRACT

The generation of tip vortices from finite-span lifting surfaces degrades the overall effectiveness of these surfaces. An extensive literature survey pertaining to this viscous rollup phenomenon and the numerous concepts advanced for its alleviation has been made. Those concepts which appear applicable to delaying the formation of marine propeller tip vortex cavitation are highlighted, and further experimental investigations are recommended.

## ADMINISTRATIVE INFORMATION

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## INTRODUCTION

On a lifting surface of finite span, the pressure difference between the pressure and the suction sides must disappear at the surface tip, so that lateral pressure gradients of opposite signs exist on these two sides. The spanwise velocity components are similarly of opposite sign, and this gives rise to trailing vortices, particularly at the wing tip, as shown in Figure 1. This tip vortex phenomenon presents special problems in practically all applications of winglike bodies, e.g., the noise and vibration caused by the interaction of the concentrated tip vortex trailed from the tip of a helicopter rotor with a following blade, and the potential hazard associated with the loss of control of light aircraft which follow in the trailing tip vortex wake of heavier aircraft. Additionally, in the case of the marine propeller, this phenomenon can lead to the situation where the local pressure in the tip vortex core reduces to the vapor pressure of the liquid, resulting in cavitation and its attendant problems.

The severity of the tip vortex problem is determined by the intensity or strength and location of tip vortices. Although numerous concepts have

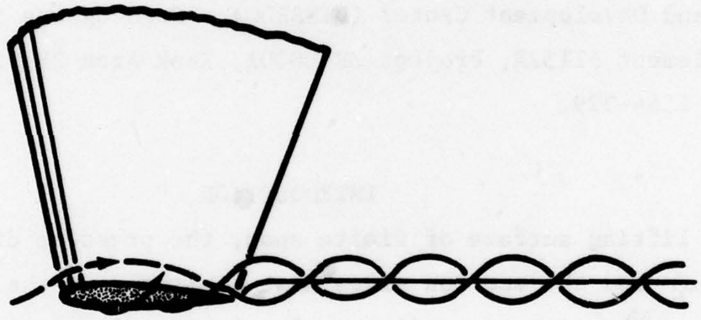

Figure 1 - Tip-Vortex Rollup Process

been advanced for the alleviation of this phenomenon, no fundamental solution to the problem is yet feasible because the details of the complex flow are not known, and the analytical tools have not yet been developed to provide design guidlines. As a result, a majority of the work in this area is fragmented and empirical in nature, being guided primarily by intuition and observation; the results cannot usually be generalized and are restricted to the specific application or investigation.

The present study attempts to identify, through an extensive literature survey, the work pertinent to the tip vortex rollup phenomenon and its alleviation. Over 150 documents are identified and cataloged. In addition, those alleviation concepts which hold promise for the delay of tip vortex cavitation on marine propellers are given closer consideration, and appropriate experimental investigations are recommended.

## BRIEF DESCRIPTION OF TIP VORTEX LITERATURE

The large volume of literature devoted to the tip vortex rollup phenomenon attests to both the importance of the associated problems and the lack of a fundamental understanding of the mechanism involved. Approximately 60 percent of the papers reviewed in the present survey represent experimental work which attempts to define the nature of the rollup process. Although the results of these investigations have begun to identify the pertinent parameters governing the vortex rollup process, they have not provided the generalized tools necessary for its prediction. As a result, the remaining 40 percent of the papers reviewed comprise experimental studies which are directed solely to the solution of the tip vortex problem. The literature dealing with the analytical representation of the viscous rollup will be reviewed in the next section.

A bibliography of all the literature reviewed is given in the Appendix. In addition, a capsuled highlight of each of the bibliography references is given in Table A1 of the Appendix. As seen in the Appendix, the large volume of tip-vortex-related literature offers very little information with regard to marine propellers, and particularly to tip vortex cavitation. Of the 40 percent of the literature dealing with tip vortex alleviation

concepts, only a few papers consider the marine propeller. In fact, a majority (over 80 percent) of the work in this area is associated directly with the aircraft industry. However, although the particular applications are quite different, the results of the aircraft tip vortex alleviation work can be applied, to varying degrees, to the marine propeller. The limits of applicability and the disparities in the literature will be highlighted in later sections of this report.

## REPRESENTATION OF TIP VORTEX ROLLUP

The earlier attempts--Lamb and Prandtl--to represent the complex vortex rollup phenomenon generally consisted of a simplified, two-dimensional, inviscid theory, where a vortex sheet emanates from the trailing edge of a lifting wing and rolls up, in the form of a spiral, under the action of its self-induced velocity field. The initial strength of the vortex sheet is determined by the spanwise load distribution of the wing. This over-simplified model failed to correctly predict the sizes and strengths of the observed vortices. As more experimental data emerged, later models became more realistic and elaborate; for example, these models began to incorporate both the viscous effects[1*] governed by the wing-tip boundary layer and an observed axial velocity[2] in the vortex core, which basically introduced a three dimensionality to the models. A recent vortex core representation,[1] shown in Figure 2, includes four distinct regions: (1) a viscous inner region, (2) a smoothed-out spiral where the velocity distribution is essentially inviscid, (3) a tightly wound spiral, and (4) an external region containing the unrolled portion of the vortex sheet.

Some results from this theory[1] are compared with experiment[3] in Figure 3, which shows the variation of the vortex core axial velocity $w_0$ with Reynolds number $R_n$. The observed disagreement is not totally unexpected since the theory is confined to laminar flow, which renders comparison with high-Reynolds-number, turbulent-flow, wind-tunnel experiments somewhat uncertain. In addition, these models are limited to very simple wing planform and loading distribution. Recently, numerical techniques[4] have

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*A complete listing of references is given on page 59.

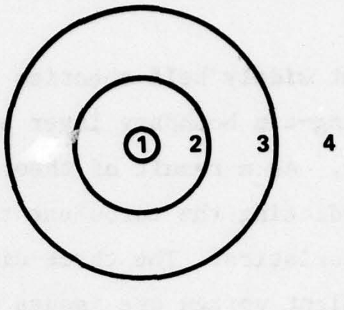


**Figure 2 - Proposed Spatial Distribution of Vortex Structure: 1 - Viscous Inner Region; 2 - Smoothed-Out Spiral, Velocity Distribution Essentially Inviscid; 3 - Tightly Wound Spiral; and 4 - Unrolled Portion of Vortex Sheet**

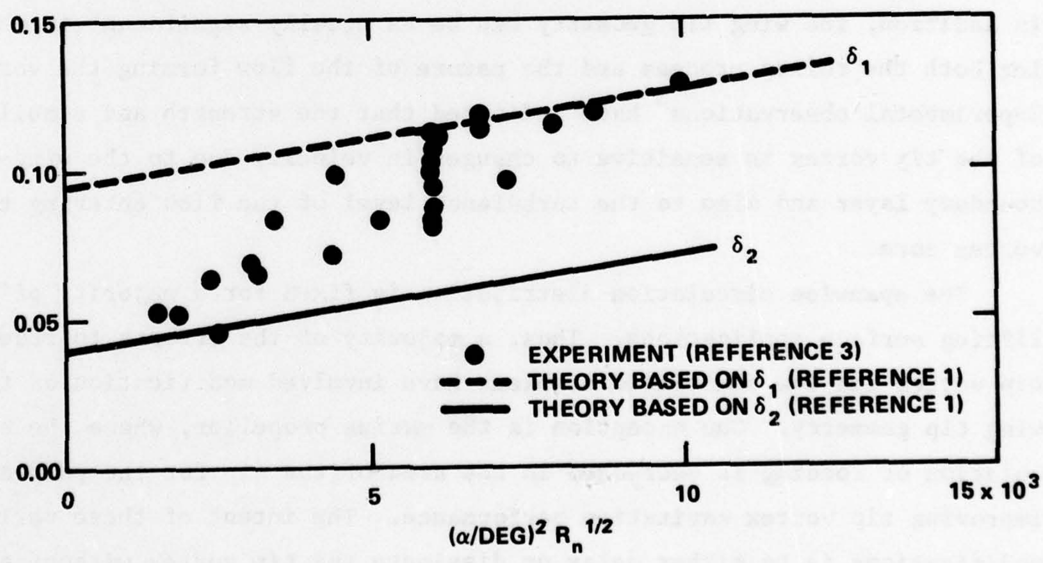


**Figure 3 - Variation of Tip-Vortex Core Axial Velocity $w_0$ with Reynolds Number $R_n$**

been employed to predict the fully rolled up vortex sheet. However, judgement must wait until some initial computational difficulties are resolved.

In summary, the most widely held theories for tip vortex rollup involve the role of the wing-tip boundary layer and assume a laminar vortex structure for simplicity. As a result of theoretical deficiencies, the models fall short of predicting the turbulent tip vortex rollup and the resulting vortex characteristics. The three-dimensional aspects of the crossflows and the turbulent vortex are issues which remain unsolved and await further study.

Although the theoretical representations are still evolving, the results of these analytical efforts, to date, in conjunction with the experimental observations, offer an insight to a general understanding of the viscous rollup process. The two common parameters identified as governing the formation of the tip vortex are:

- the spanwise distribution of the lifting surface circulation, and
- the detailed configuration of the lifting surface tip geometry.

Both the magnitude and distribution of the spanwise circulation directly control the basic shape and strength of the resulting tip vortex. In addition, the wing tip geometry can be as equally significant in changing both the rollup process and the nature of the flow forming the vortex. Experimental observations[5] have indicated that the strength and stability of the tip vortex is sensitive to changes in velocity due to the wing-tip boundary layer and also to the turbulence level of the flow entering the vortex core.

The spanwise circulation distribution is fixed for a majority of the lifting surface applications. Thus, a majority of the efforts to reduce the tip vortex and the associated problems have involved modification of the wing tip geometry. One exception is the marine propeller, where the circulation or loading is decreased in the area of the tip for the purpose of improving tip vortex cavitation performance. The intent of these various modifications is to either delay or dissipate the tip vortex without an unreasonable penalty in efficiency. The remainder of the present study will involve a discussion of these various concepts and their potential applicability to the marine propeller and tip vortex cavitation.

## TIP VORTEX ABATEMENT CONCEPTS

### SCHEMES PROPOSED IN THE LITERATURE

The literature identifies approximately twenty concepts for alleviating tip vortex. These concepts, some of which are shown in Figure 4, generally involve wing tip modifications. Table 1 identifies the bibliography listing with the particular concept considered. Comparison of the relative merits between concepts is difficult due to differences in the experimental procedures, the recorded data, and the operational Reynolds number $R_n$.

Figure 5 shows the range of investigative Reynolds number $R_n$ and angle of attack $\alpha$ for the various concepts shown in Figure 4. The majority of these investigations were performed in low-speed wind tunnels and involved far-field wake surveys of vorticity generated by planar wings. Approximately one-half of the investigations include some force data to determine the efficiency of the concept. Only a small percentage of the studies were performed in water and recorded cavitation data.

In light of the above findings, it is apparent that the results of the literature offer very limited guidance when considering the problems of delaying tip vortex cavitation on a marine propeller. The crucial cavitation inception data and the wing near-field wake data are generally not available. In addition, for application to marine propellers, any concept must be evaluated with regard to certain practical aspects, e.g., structural suitability, reliability, and operational environment. Also, the concept should not be a source of any additional local cavitation and should not introduce prohibitive performance penalties. These requirements should be kept in mind as the details of the various concepts are discussed.

### SPANWISE LOAD DISTRIBUTION

The strength of the tip vortex is strongly dependent on the magnitude of the spanwise load distribution near the tip. As the loading shifts inboard, away from the tip, the tip vortex strength decreases. This is accomplished for aircraft through the use of wing flaps, which effectively change the wing aspect ratio, and for propeller blades through appropriate

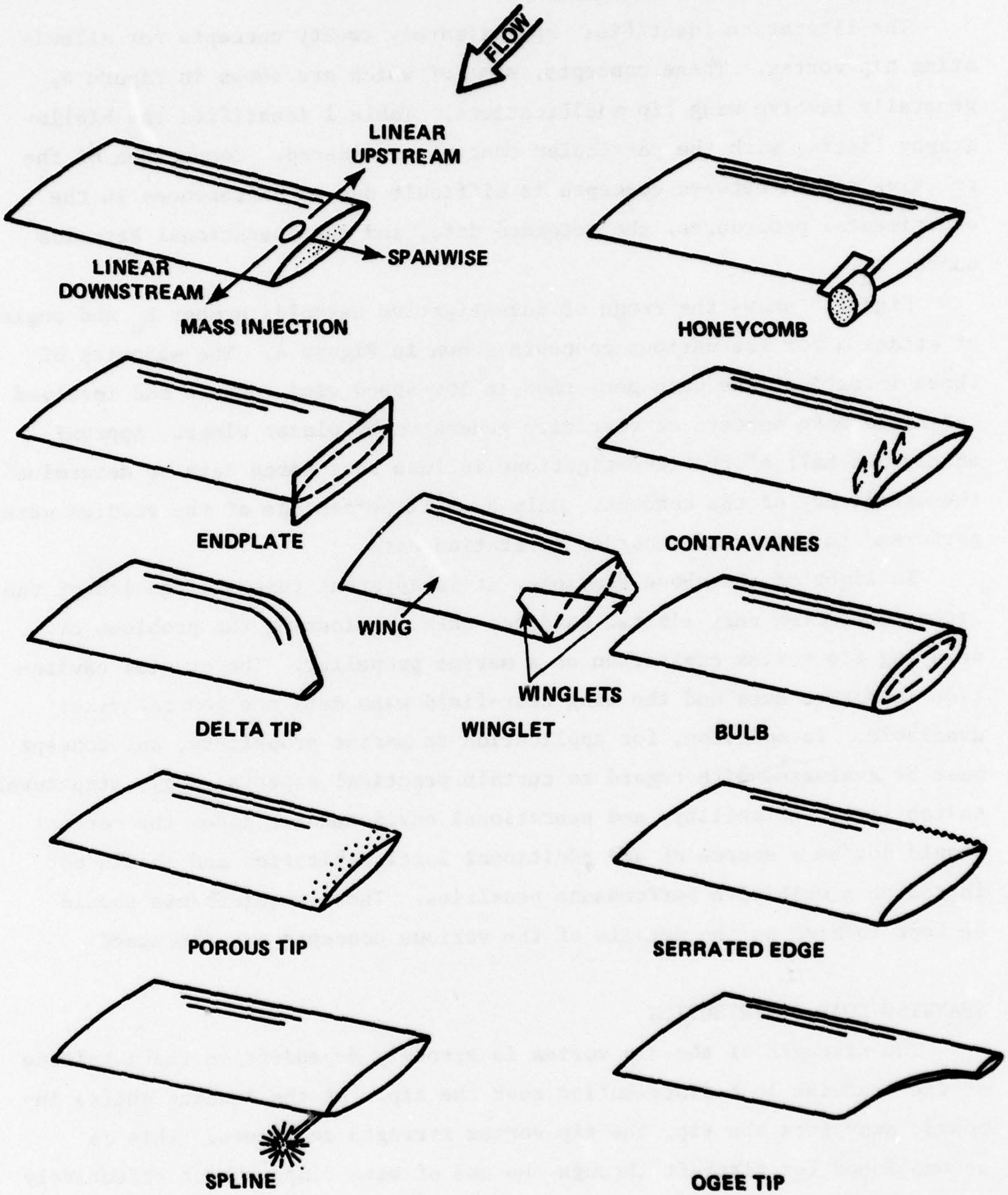


Figure 4 - Illustration of Schemes for Alleviating Tip Vortex

TABLE 1 - LISTING OF CONCEPTS PROPOSED TO ALLEVIATE TIP VORTEX AND THE NUMBERED BIBLIOGRAPHY ENTRY IN WHICH THE CONCEPT IS PROPOSED

| Vortex Alleviation Concept | No. of Times Proposed | Bibliography Entry No. (see Appendix A) |
|---|---|---|
| Spanwise Loading | 2 | 29, 125 |
| Planform: Delta, Sweep, etc. | 9 | 15, 27, 32, 33, 35, 41, 98, 125, 130 |
| OGEE | 3 | 1, 73, 109 |
| Edge Detail | 5 | 22, 57, 131, 132, 142 |
| Honeycomb | 1 | 125 |
| Bulbous Tip | 1 | 36 |
| Serrated Edge | 2 | 123, 124 |
| Tip Duct | 1 | 125 |
| Porous Tip | 5 | 119, 121, 125, 130 |
| Endplate | 2 | 57, 130 |
| Drooped Wing | 1 | 87 |
| Fence | 1 | 83 |
| Contravanes | 1 | 125 |
| Tip Spoiler | 4 | 30, 35, 130, 148 |
| Splines | 3 | 35, 83, 101 |
| Mass Injection | 12 | 1, 59, 61, 64, 84, 106, 120, 122, 125, 142, 147, 148 |
| Winglet | 1 | 92 |

## Figure 5 - Investigative Ranges

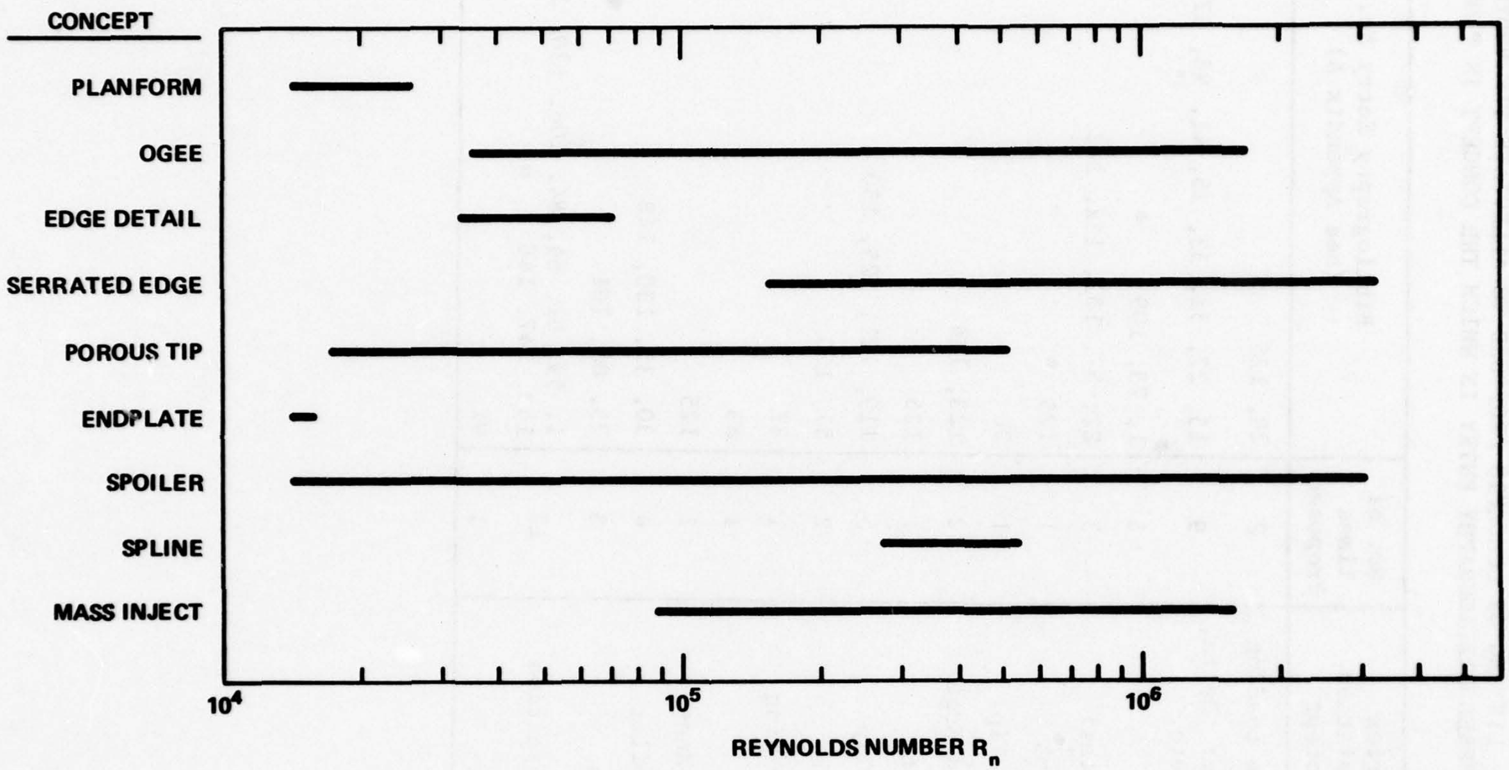


Figure 5a - Reynolds Number $R_n$ for the Various Concepts

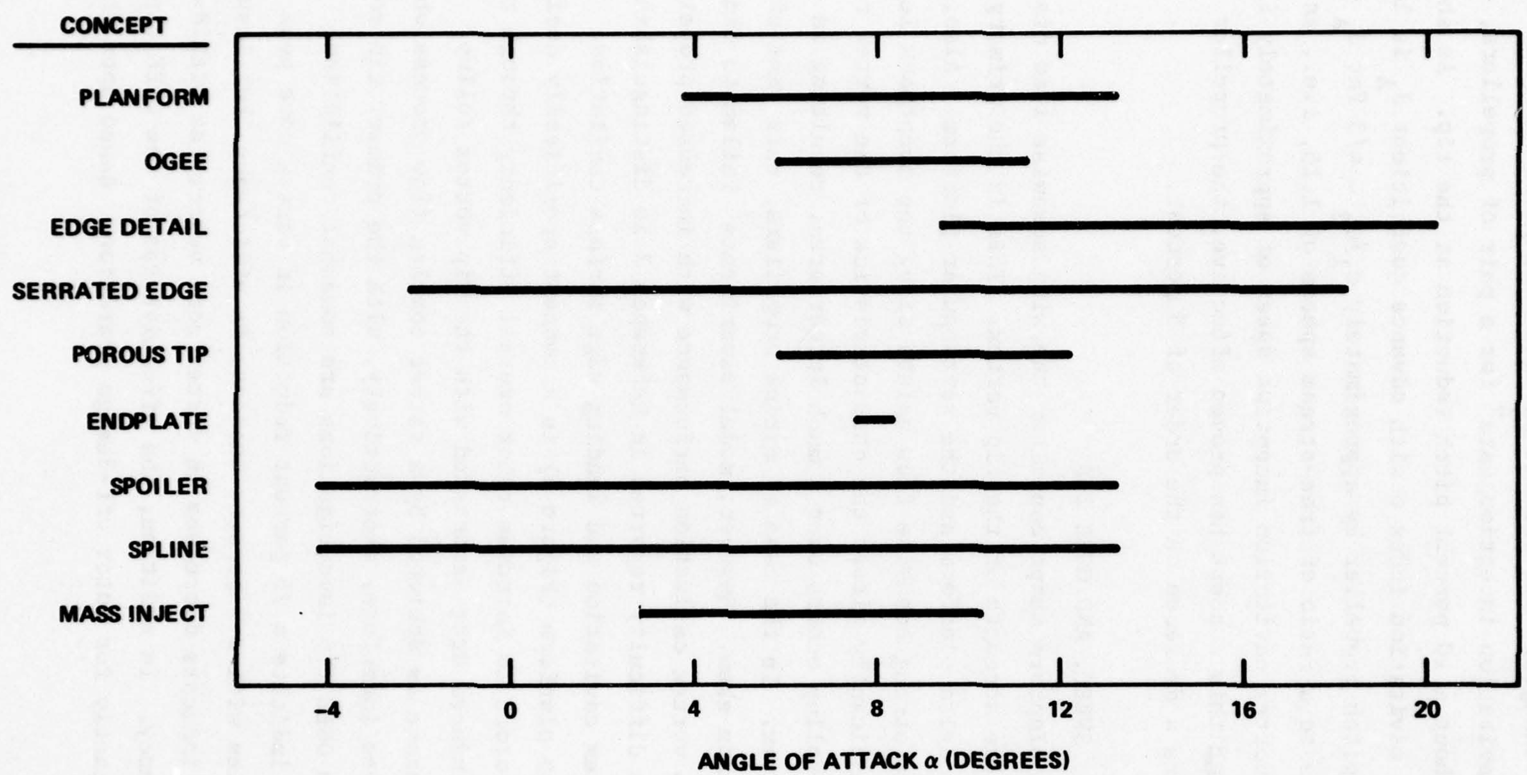


Figure 5b - Angle of Attack α

pitch and camber changes. The benefit of this concept is shown in Figure 6 which presents cavitation inception data[6] for a pair of propellers, one with and one without a 10 percent pitch reduction at the tip. As shown, the variation of cavitation index $\sigma$ with advance coefficient $J_A$ is lower for the reduced pitch propeller by approximately $\sigma_1/\sigma_2 \sim 4/3$ for $J_A = 0.80$, which corresponds to a ratio of free-stream speeds of 1.15, i.e., an increase in tip vortex cavitation inception speed of approximately 15 percent. Although this concept has proven effective, the propeller efficiency suffers a decrease on the order of 5 percent.

PLANFORM: DELTA, SWEEP, AND OGEE TIP

A change in planform shape can alter the wing spanwise load distribution, and hence the strength of the tip vortex. This is the primary difference between the delta planform and the rectangular planform. Also, for the delta planform, a strong spanwise flow exists along the sweptback leading edge, which significantly alters the characteristics of the vortex rollup. Apparently, the rollup occurs over a much larger area, resulting in a less concentrated vortex. In the case of marine propellers, this same effect is obtained with blade skew. However, model experiments[7] failed to demonstrate any improved tip vortex cavitation performance with increased propeller blade skew. One difficulty reported in Reference 7 is distinguishing between tip vortex cavitation and leading edge surface cavitation.

The OGEE tip planform (Figure 4) is a concept specifically designed for helicopter rotors to increase rotor overall efficiency through reduction in the induced drag associated with the tip vortex rollup. This improved performance is achieved by a rather complex flow process where secondary vortices interfere, destructively, with the primary tip vortex. The results from OGEE tip investigations are somewhat conflicting: optimistic reports[8] indicate a 75 percent reduction in vortex core peak tangential velocities with a 5 percent increase in efficiency, but less optimistic reports[9] indicate decreases in vortex core velocities with decreases in rotor efficiency. In addition, the effectiveness of the OGEE tip is reduced significantly for rotor off-design operation. Based upon the

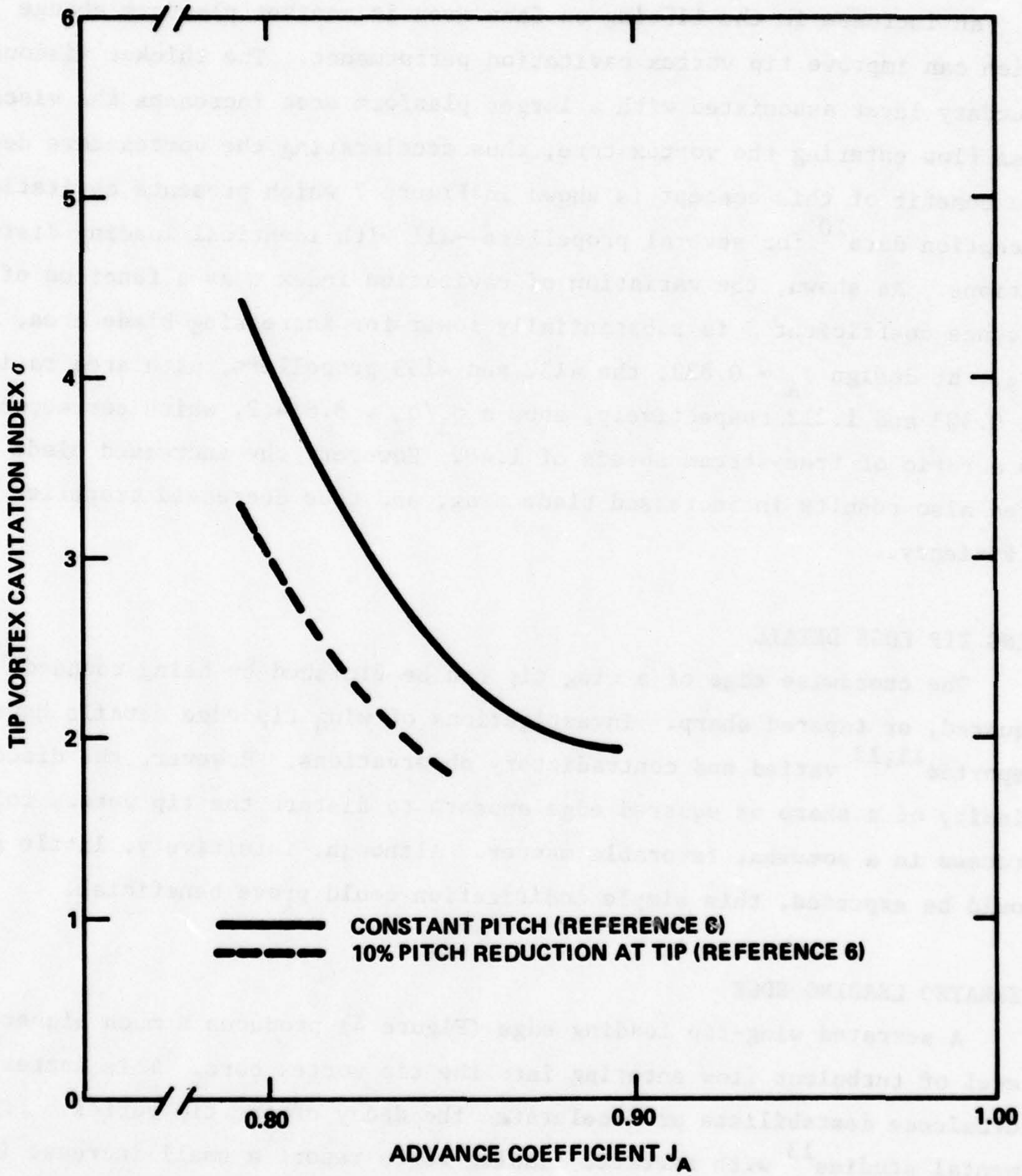


**Figure 6 - Variation of Propeller Tip Vortex Cavitation Index σ with Advance Coefficient $J_A$, with and without Tip Pitch Reduction**

**(Data from Reference 6)**

questionable performance limitation, the adaptation of an OGEE tip planform to a marine propeller appears, at best, marginal.

An increase in the lifting surface area is another planform change which can improve tip vortex cavitation performance. The thicker viscous boundary layer associated with a larger planform area increases the viscous mass flow entering the vortex core, thus accelerating the vortex core decay. The benefit of this concept is shown in Figure 7 which presents cavitation inception data[10] for several propellers--all with identical loading distributions. As shown, the variation of cavitation index $\sigma$ as a function of advance coefficient J is substantially lower for increasing blade area, e.g., at design $J_A = 0.833$, the 4132 and 4133 propellers, with area ratios of 0.303 and 1.212 respectively, show a $\sigma_1/\sigma_2 \sim 8.8/4.2$, which corresponds to a ratio of free-stream speeds of 1.40. However, the increased blade area also results in increased blade drag, and thus decreased propeller efficiency.

## WING TIP EDGE DETAIL

The chordwise edge of a wing tip can be finished by being rounded, squared, or tapered sharp. Investigations of wing tip edge details have reported[11,12] varied and contradictory observations. However, the discontinuity of a sharp or squared edge appears to disturb the tip vortex rollup process in a somewhat favorable manner. Although, intuitively, little gain would be expected, this simple modification could prove beneficial.

## SERRATED LEADING EDGE

A serrated wing-tip leading edge (Figure 4) produces a much higher level of turbulent flow entering into the tip vortex core. This increased turbulence destabilizes or accelerates the decay of the tip vortex. Experimental studies[13] with serrated leading edges report a small increase in wing efficiency for small angles of attack and identify the serration size and density as important parameters. The adaptation of this concept to the marine propeller would likely produce additional local cavitation.

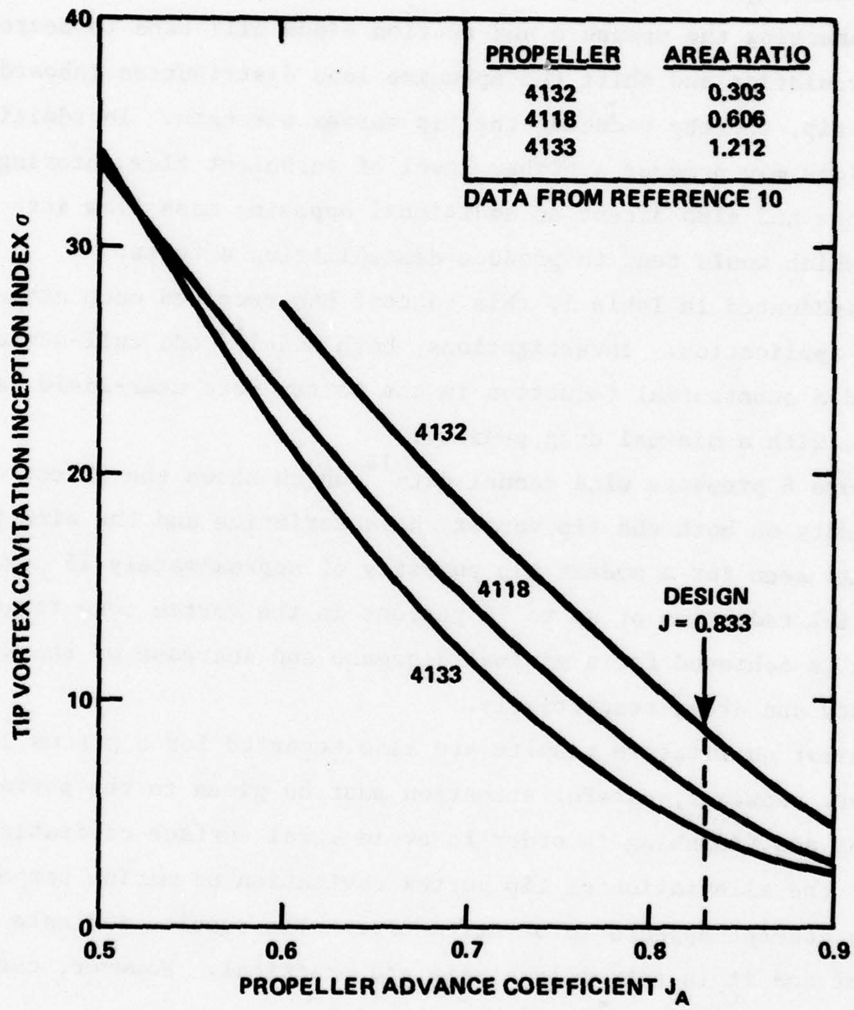


**Figure 7 - Variation of Propeller Tip Vortex Cavitation Index as a Function of Advance Coefficient for Various Propeller Area Ratios (Data from Reference 10)**

## POROUS TIP

Wing tip porosity refers to perforations, of varying size, distribution, and density, which connect the pressure and suction sides of the lifting surface tip. The porosity concept may produce several beneficial effects with regard to delay of tip vortex cavitation, e.g., the perforations connecting the pressure and suction sides will tend to decrease the local circulation and shift the spanwise load distribution inboard, away from the tip, thereby reducing the tip vortex strength. In addition, the perforations may produce a higher level of turbulent flow entering the vortex core and also direct an additional opposing mass flow into the core, both of which would tend to produce destabilizing effects.

As indicated in Table 1, this concept has received much attention for aircraft application. Investigations, both model[14] and full-scale,[15] have indicated a substantial reduction in the vortex core near-field tangential velocity, with a minimal drag penalty.

Figure 8 presents wind tunnel data[14] which shows the effect of wing tip porosity on both the tip vortex characteristics and the wing performance. As seen for a modest tip porosity of approximately 15 percent, a substantial reduction of up to 70 percent in the vortex core tangential velocity is achieved for a minimal decrease and increase of the wing efficiency and drag, respectively.

Similar qualitative results are also reported for a porous tipped propeller. However, careful attention must be given to the perforation alignment and finishing in order to avoid local surface cavitation

For the alleviation of tip vortex cavitation on marine propellers, the porosity concept appears to be attractive. The results indicate that it is efficient and it is extremely simple and practical. However, care must be exercised to avoid local surface cavitation.

## ENDPLATES, WINGLETS, FENCES, AND CONTRAVANES

The attachment of vertical endplates to the wing tip (Figure 4) significantly interferes with the tip vortex rollup. Numerous investigations report that the endplate retards the rollup, thereby increasing the tip loading. In addition, the increased endplate surface area tends to disperse

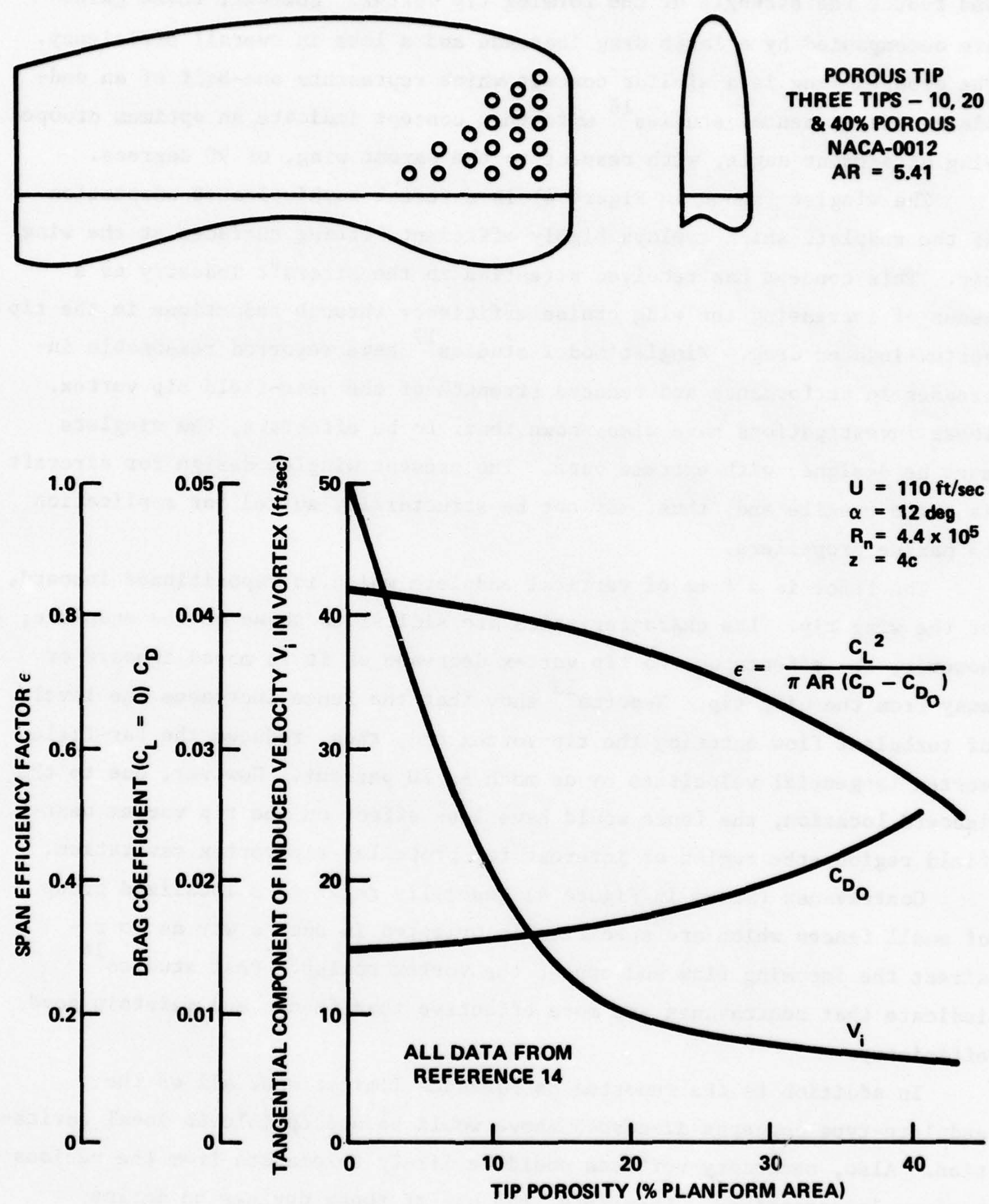


Figure 8 - Variation of Efficiency ε, Drag Coefficient $C_D$, and Core Tangential Velocity $V_i$ with Tip Porosity for a Porous Tip Wing

(Data from Reference 14)

and reduce the strength of the forming tip vortex. However, these gains are accompanied by a large drag increase and a loss in overall efficiency. The drooped wing is a similar concept which represents one-half of an endplate. Experimental studies[16] with this concept indicate an optimum drooped wing attachment angle, with respect to the parent wing, of 90 degrees.

The winglet (shown in Figure 4) is a recent sophisticated adaptation of the endplate which employs highly efficient lifting surfac at the wing tip. This concept has received attention in the aircraft industry as a means of increasing the wing cruise efficiency through reductions in the tip vortex-induced drag. Winglet model studies[17] have reported reasonable increases in performance and reduced strength of the near-field tip vortex. These investigations have also shown that, to be effective, the winglets must be designed with extreme care. The present winglet design for aircraft is quite fragile and, thus, may not be structurally suited for application to marine propellers.

The fence is a form of vertical endplate which is repositioned inboard, of the wing tip. Its characteristics are similar to those of the endplate; however, the effects on the tip vortex decrease as it is moved inboard or away from the wing tip. Reports[18] show that the fence increases the level of turbulent flow entering the tip vortex and, thus, reduces the far-field vortex tangential velocities by as much as 70 percent. However, due to the inboard location, the fence would have less effect on the tip vortex near-field region--the region of interest for propeller tip vortex cavitation.

Contravanes (shown in Figure 4) generally refer to a localized group of small fences which are specifically oriented in such a way as to redirect the incoming flow and oppose the vortex rollup. Past studies[14] indicate that contravanes are more effective than fences and maintain good efficiency.

In addition to the reported performance limitations, all of the endplate-type concepts discussed above would be susceptible to local cavitation. Also, secondary vortices would be likely to emanate from the various surface intersections. Therefore, the use of these devices on marine propellers appears questionable.

## BULBOUS TIP

A wing tip bulb is defined as any selective increase in the wing tip thickness, e.g., aircraft wing tip tanks or pods. The thicker tip viscous boundary layer associated with the bulb increases the viscous mass flow entering the vortex core, thus destabilizing or dissipating the vortex core energy. In addition, the bulb may act in a manner similar to an endplate and retard the tip vortex rollup process.

The bulbous tip concept has been applied, with varying degrees of success, to both model and full-scale[19] marine propellers. The benefit of this device is shown in Figure 9, which presents cavitation inception and efficiency data[19] for a pair of model propellers, one without and one with a tip bulb of thickness approximately 2 percent of the propeller diameter. As shown, the variation of cavitation inception index $\sigma$ as a function of advance coefficient $J_A$ is substantially lower for the bulbous tip propeller; e.g., for $J_A \sim 0.65$, $\Delta\sigma \sim 7.5$, which corresponds to a ratio of free-stream speeds of 1.4. The bulbous tip propeller suffers a maximum decrease in efficiency $\eta_0 \sim 4.5$ percent.

The results from the bulbous tip work appear promising, and the bulb may prove to be a viable concept for delaying tip vortex cavitation inception. However, the bulb must be carefully designed to minimize both local cavitation and efficiency loss.

## TIP DUCT

The tip duct consists of a faired tube attached to the transverse or chordwise edge of the wing tip. The duct outer surface acts similar to the bulbous tip, while the inner surface tends to destabilize the vortex core by retarding the core entry flow. Also, reverse swirl vanes can be added inside the duct in an attempt to induce rotational velocities to oppose the vortex rollup. Tip duct investigations[14] report only modest increase in effectiveness with a large increase in drag. Thus, this device does not appear to be suited for the marine propeller.

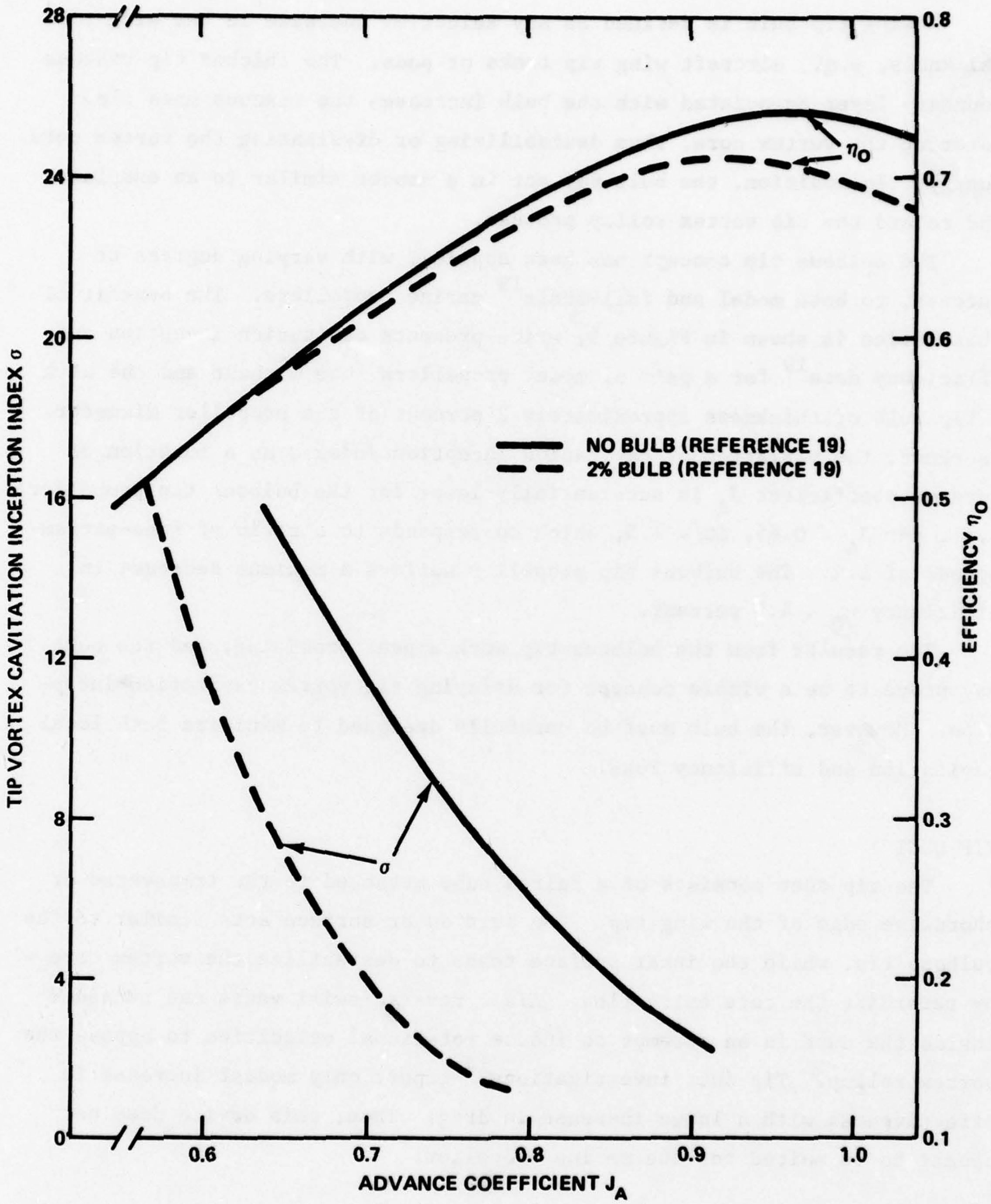


Figure 9 - Variation of Cavitation Index σ as a Function of Advance Coefficient $J_A$ for the Bulbous Tip Propeller

(Data from Reference 19)

## TIP SPOILER

The tip spoiler is similar to a fence, except that it is oriented in a spanwise manner, perpendicular to the incoming flow. Spoilers can be located at various chordwise locations on the wing pressure or suction side, but ideally the location should be such that the spoiler-increased turbulent flow is absorbed directly into the vortex core, thereby dissipating the vortex core energy.

The numerous tip spoiler investigations generally concur that this device is highly effective; e.g., some reports[20] claim an 80 percent reduction in the tip vortex circulation strength, while others[21] indicate that a small tip spoiler may be as effective as a much larger one, with substantially less parasitic drag. However, there also is a large discrepancy in the reported spoiler drag--from negligible to prohibitive. Again, based upon the possible performance penalty and the potential for local surface cavitation, spoilers hold little promise for application to propellers.

## TRAILING EDGE DEVICES: SPLINES AND HONEYCOMB

Splines and honeycomb (shown in Figure 4) represent trailing edge devices which are located off the wing and just aft of the wing-tip trailing edge. These devices are positioned in the path of the tip vortex, the intent being to destroy the vortex structure and promote early decay. Recent investigations involving the application of these concepts to weaken large aircraft vortex wakes report[14,18] a high degree of effectiveness, but also an equally high increase in drag.

The trailing edge devices operate in the downstream tip vortex wake region and, as such, do not affect either the rollup process on the wing or the tip vortex structure in the wing near field. On this basis, it appears that these devices would have little, if any, effect on the inception of tip vortex cavitation. In addition, for marine propeller application, these concepts would suffer obvious structural limitations.

## TIP MASS INJECTION

As implied by the title, tip mass injection involves the ejection of a fluid in the vicinity of the wing tip vortex. Of all the devices reviewed,

this one has received the greatest attention (see Table 1). Basically, three mass ejection techniques are reported in the literature: linear or axial mass ejection, directly into the vortex core, with either an (a) upstream or (b) downstream facing jet, and (c) spanwise mass ejection with an outboard facing jet. These injection schemes are illustrated in Figure 4. Linear mass ejection increases the core axial pressure and accelerates the vortex decay through the viscous interaction of the two flows. Spanwise mass ejection blocks or interrupts the vortex rollup as it forms along the tip chord and results in improved wing performance.

Linear mass ejection studies[22,23] have repeatedly demonstrated the concept effectiveness with regard to dissipation of the vortex core energy with little or no effect on performance. The results of some linear mass ejection wind tunnel studies[22] are given in Figure 10 which shows the variation of vortex core relative vorticity intensity $\Omega/\Omega_0$ as a function of jet momentum coefficient $C_j$ with both an upstream and downstream facing jet, for various values of $z/c$. As indicated, for fixed values of $C_j$ the upstream facing jet appears to be more effective in reducing the vortex vorticity than the downstream one. However, the upstream configuration would require higher delivery pressures in order to overcome the opposing free-stream stagnation pressure.

Spanwise mass ejection has been shown[24] to be an effective means of altering tip vortex rollup and increasing wing performance. As shown in Figure 11, the spanwise ejection data[24] indicate that, within one chord length downstream of the wing trailing edge, the peak rotational velocity is reduced by approximately a factor of 5, and the vortex sheet wrapup has been delayed beyond one chord length downstream. This is accompanied by an induced drag reduction of approximately 15 percent at operational lift coefficients. Although these results are impressive, the spanwise mass ejection rates are an order of magnitude higher than the corresponding linear rates.

There is little data on the correlation between the water mass ejection rates required to delay tip vortex cavitation and the reported air mass rates required to reduce vortex core vorticity. Nevertheless, tip

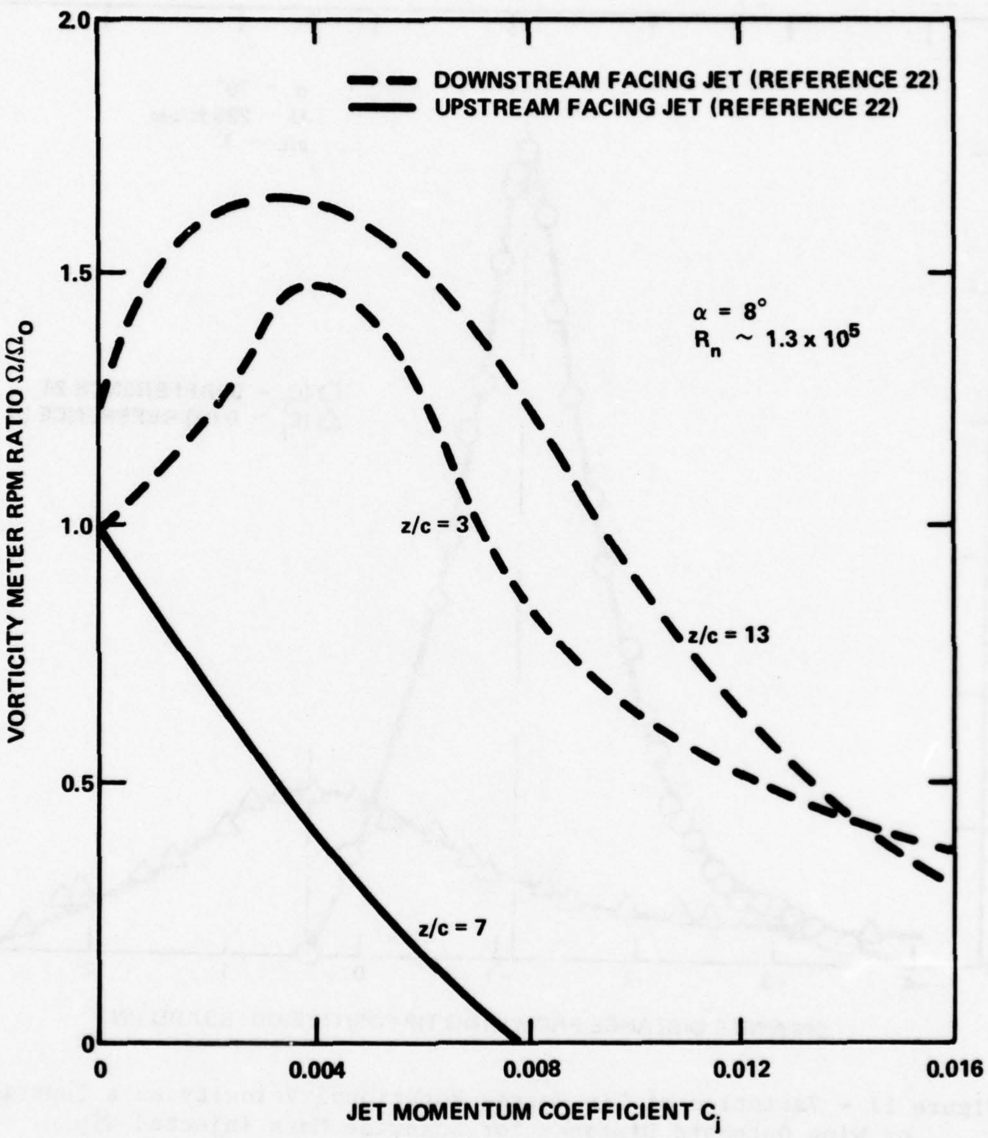


Figure 10 - Variation of Tip Vortex Vorticity as a Function of Jet Momentum Coefficient $C_j$ for Linear Mass Injected Tip

(Data from Reference 22)

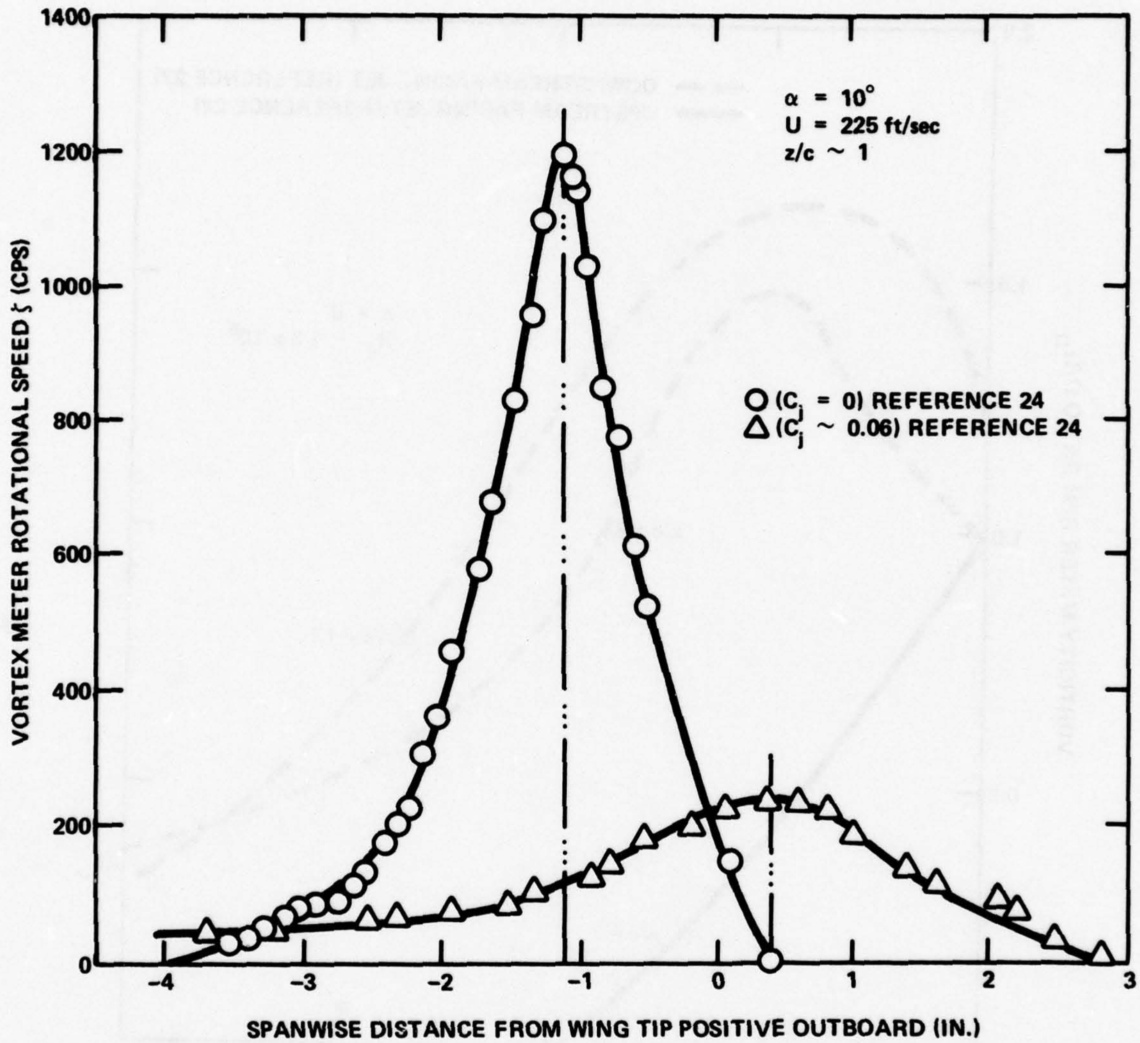


Figure 11 - Variation of Tip Vortex Rotational Velocity as a Function of Wing Outboard Distance for Spanwise Mass Injected Tip

(Data from Reference 24)

mass ejection, especially linear, may prove to be an effective means of delaying tip vortex cavitation on marine propellers. Practically, the concept will be limited by the required delivery power, which will be aided by the centrifugal action of the propeller.

## OTHER CONCEPTS

There are other tip vortex dissipation concepts which are not reported in the literature, e.g., elastic and flow separation tips and large tip skew. All of these ideas address the propeller nonhomogenous wake environment and would tend to delay tip vortex cavitation by averaging the unsteady blade loading--i.e., by avoiding the unsteady high lift conditions, the unsteady tip vortex cavitation would be reduced. Both an elastomer tip section designed to deform to reduce camber and a flow separation tip section designed to have separation, at angles of attack larger than design, would present a more constant loading for a given wake variation. However, flow-separation-related cavitation may be a limitation here. Similarly, large tip skew, applied to that area of the blade span which directly controls the vortex rollup, would also tend to average the unsteady propeller loading due to wake nonuniformity. This idea could suffer possible structural limitations as a result of increased blade stresses.

One final thought, a very recent, but not yet reported, concept aimed at delaying vortex cavitation involves the application of a localized artificial surface roughness in the area of the wing tip. Earlier qualitative studies[5] have shown that a roughened surface on the pressure side of the wing tip can reduce the tip vortex cavitation inception index $\sigma$ by approximately 20 percent. This lends support to the earlier hypothesis that the thickness of the wing tip viscous boundary layer plays an important role in the occurrence of tip vortex cavitation. Although no supporting performance data are available, this idea may warrant pursuit.

## SUMMARY AND CONCLUSIONS

As mentioned earlier and reinforced in the above discussions, the large body of literature dealing with tip vortex delay offers limited guidance

when considering the effectiveness of a particular device to delay tip vortex cavitation on a marine propeller. The primary problem is that most of the studies are performed in air and involve investigations of the wing far-field wake. The crucial cavitation inception and performance data and the wing near-field wake data are generally not available. However, even with these limitations, the aircraft tip vortex alleviation work can provide some insight. For example, the trailing edge devices (splines and honeycomb) designed to mechanically destroy the tip vortex structure are subject to high drag and reduced efficiency; similarly, planform changes designed to thicken the tip boundary layer and increase tip vortex decay may, if not carefully designed, alter the spanwise loading and result in decreased efficiency; and, practically, all of these aircraft "add-on" devices are susceptible to local cavitation. One additional consideration which deserves mention: the marine propeller usually operates in a nonhomogenous wake and experiences a large angle of attack variation which results in rather dramatic changes in blade loading. Thus, any potential concept should also provide a reasonable degree of effectiveness for off-design operation. This requirement would tend to render less attractive such devices as the OGEE tip and endplates.

In view of the foregoing discussions of the various devices and the additional requirements imposed for marine propeller application, three concepts appear to warrant further consideration with regard to their potential for delaying marine propeller tip vortex cavitation. They are

- the bulbous tip
- the porous tip
- the linear mass injection tip.

All of these candidates have been shown to be effective an reasonably efficient.

The bulbous tip which represents the only concept with supporting cavitation inception data, has been shown to delay tip vortex cavitation on marine propellers with a small-to-modest efficiency loss. Optimization of the bulb design should result in additional improved performance.

Similarly, the porous and linear mass ejection tips, with supporting data based only upon air studies, have been shown to significantly alter

and enhance tip vortex decay, with little or no efficiency loss. For the porous tip, care must be exercised in the perforation design to avoid local cavitation, while for the mass ejection tip, the mass flows must be minimized to be practical.

Until improved analytical representation of the tip rollup process is realized, progress in this area must be made through empirical means. Thus, it is recommended that an experimental investigation be initiated to assess the potential of the above candidate tip vortex alleviation concepts. The investigative Reynolds number $R_n$ should be as high as possible, using large models, in order to minimize uncertainties when extending the model results to full-scale. In addition, the study should be conducted in a cavitation tunnel with an appropriate force dynamometer in order to provide the necessary tip vortex cavitation inception and performance data. Due to both a lack of existing data and a physical understanding, it would be prudent to keep the initial experimental effort fundamental and simple, employing, say, a fixed planar lifting surface. The particular concept adaptation to a propeller could come at a later stage. However, the parameters which tend to control the tip vortex rollup on a propeller blade should also be incorporated into the fixed planar foil: e.g., the geometric planform, especially the tip area, and the spanwise circulation or loading distribution. A representative planform would, obviously, be ellipitical, while the loading distribution should be similar to that of the outer portion of a typical marine propeller (e.g., see Figure 12). Finally, the investigative angle-of-attack range should be sufficient to evaluate the candidate concept performance for off-design operation.

In conclusion, an attempt has been made to survey the pertinent literature dealing with the tip vortex rollup phenomenon and, especially, its alleviation. The major dissipation concepts have been briefly discussed. Those few which appear adaptable for delaying tip vortex cavitation in marine propellers are identified, and appropriate experimental investigations are recommended. The candidate concepts would appear to offer better tip vortex performance than is obtainable through the present technique of propeller spanwise unloading alone.

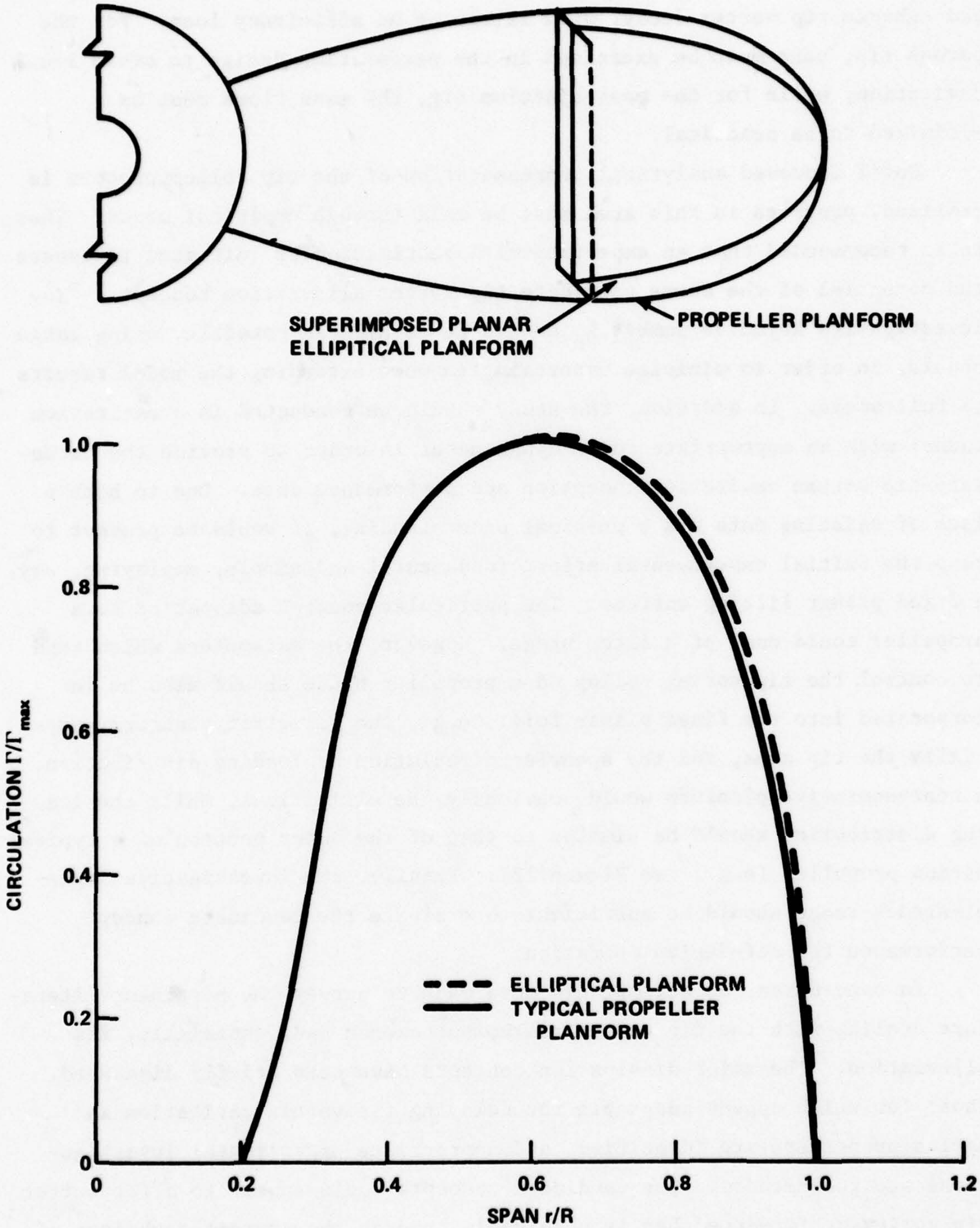


**Figure 12 - Comparison of Spanwise Loading for a Fixed Planar Elliptical Planform Foil and a Typical Propeller Blade-Variation of Circulation ($\Gamma/\Gamma_{max}$) as a Function of Span (r/R)**

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# APPENDIX

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## Table A1 - Highlights of the Bibliography

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM: AIR | MEDIUM: WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | √ | Helicopter Rotor Blades | √ | √ | | | | Wind Tunnel √ | Measured circulation strength as function of thrust and mass flow rate. Flow visualization via smoke, helium bubbles, and tuft grids. | Demonstration of vortex dissipation using mass injection. Also effect of OGEE tip given. |
| 2 | √ | | | √ | | | | | | | Finite-diff.-element model for turbulent vortex, compared to approximation methods. |
| 3 | √ | | | | | | | | | | Finite-difference code for the wake-vortex problem, in quasi-cylindrical boundary layer approximation. Turbulent energy model. |
| 4 | √ | | | √ | | | | | | | Analytical account, in general terms, for the strong axial current in the vortex core. |
| 5 | √ | | | √ | √ | | | | | | Examines abrupt structural change of vortex core, analogous to hydraulic jump. |
| 6 | √ | √ | | | √ | | | √ | | Wake measurements with 5-hole pitot tube and hot-film anemometer. | Describes 5-year ARAP analytical and experimental program dealing with generation and decay of aircraft wake turbulence. |
| 7 | √ | | | √ | √ | | | | | | Nonlinear model developed to demonstrate the role of lift and drag distributions on the vortex wake structure. Experimental agreement. |
| 8 | √ | | | √ | √ | | | | | | Interaction of aircraft wake vortices using inviscid and viscous models. Uses 2nd-order closure model of turbulent transport. |
| 9 | | √ | | √ | | √ | √ | | | Desinent cavitation numbers for tip vortex and blade surface cavitation for a family of hydrofoils. | Develops a better understanding of vortex and surface cavitation scaling through the use of geosimilar foils. |
| 10 | | √ | | √ | | √ | √ | √ | | Noise and visual cavitation inception. | Measurement of cavity generated noise for *two-dimensional foils in water tunnel.* |
| 11 | | √ | Helicopter Rotor Blades | | √ | | | | √ | Boundary layer velocity profiles using hot-wire anemometry. | Chordwise velocity profiles showed no unusual characteristics in both hover and forward flight modes. |
| 12 | √ | | | √ | √ | | | | | | Artificial viscosity method of Kawaharra applied to several tip vortex configurations. Results compare well with experiment. |
| 13 | √ | | | | | | | | | | Vortex breakdown is feature of solution of Navier-Stokes equations for vortex structure. |

## Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | ✓ | | | ✓ | ✓ | | | | | | Computes rotational, quasi-cylindrical, viscous, incompressible vortex flow. No comparison with experiment. |
| 15 | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | Visual cavitation inception. | Effect of skew on cavitation for a series of propellers. |
| 16 | ✓ | ✓ | | ✓ | ✓ | | | | ✓ | Aircraft flyby. Hot-film, smoke-screen flow visualization. | A wake vortex transport model which includes wind and wind shear is developed. Agreement with experiment is tentative. |
| 17 | | ✓ | | ✓ | ✓ | | | | ✓ | Aircraft flyby. Hot-film, smoke-screen flow visualization. | Model given in Reference 16 developed further. Correlation with new experimental data improved. |
| 18 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Flow visualization, pitot tube boundary layer measurement, hot-wire wake velocity and turbulence. | Strong Karman vortices developed behind blunt trailing edge of plate. Disappear when upper/lower surface velocities unequal. |
| 19 | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | No measurements given, but scaling parameters presented. | Discussion of basic difference between test in air/water relative to study of aircraft wake phenomena. |
| 20 | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | Tip vortex cavitation inception; vortex core diameter measured with telescope. | A marked delay in tip vortex cavitation, as number of blades is increased, is observed (at model scale). |
| 21 | | ✓ | | ✓ | ✓ | | | | ✓ | Instrumented trailing plane measured vertical and lateral wake velocities. | Full-scale aircraft wake reveals strong vortices distinct from tip vortices. |
| 22 | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | Visual cavitation inception. | Theoretical analysis estimates structure of tip vortex, circulation distribution core radius, and critical cavitation index for hydrofoil and propeller. |
| 23 | | ✓ | | ✓ | ✓ | | | | ✓ | Photographed smoke-seeded vortex patterns off aircraft wing in flight. | Results provide verification of vortex wake instability predicted by theory. |
| 24 | | ✓ | | ✓ | ✓ | | | ✓ | | Distribution of velocity components in vortex core using a three-wire anemometer up to 12 chordlengths downstream. | Increasing drag increases vortex core radius and reduces maximum tangential core velocity. |
| 25 | | ✓ | | ✓ | ✓ | | | | ✓ | Flow visualization and hot-film measurements of aircraft flyby. | Qualitative article for general public. Some of FAA studies mentioned, including use of ground deflectors to reduce tip vortex. |
| 26 | | ✓ | | ✓ | | ✓ | | ✓ | | Measurement of tip vortex core axial velocity using laser Doppler velocimeter in water. | Presents continuous data of near- and far-field tip vortex core axial velocity. Results agree with theory. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | | ✓ | | ✓ | | ✓ | | ✓ | | Tangential and axial velocity profile in tip vortex wake with a 2-D scanning laser velocimeter. Foil lift and drag. | Identifies two distinct regions in downstream wake of wing. Change in wing loading reduces vortex tangential velocity by factor of 2. |
| 28 | ✓ | | | ✓ | ✓ | | | | | | Calculates circulation distributions which retard the vortex rollup. |
| 29 | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | Visual cavitation inception. | Effect of propeller pitch reduction on tip vortex. |
| 30 | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | Smoke and tuft flow visualization. Core velocities measured using hot-wire anemometer. | Vortex dissipator, small vertical panel on wingtip, caused significant reduction in core tangential velocities. |
| 31 | | ✓ | | ✓ | ✓ | | | ✓ | | 3-D hot-wire anemometer measured velocity on 2-D wing sections. | Results agree with Nielson + Schwind Turbulent Vortices. Shows value of anemometer for this use. |
| 32 | | ✓ | | ✓ | ✓ | ✓ | | ✓ | | Rolling moment measured on model trailing in wake. Vortex motion via flow visualization in air and water. | Reshaping span loading on a generating model substantially reduced the rolling moment on a wing trailing in the wake. |
| 33 | | ✓ | | ✓ | | ✓ | ✓ | ✓ | | Visual cavitation inception. Drag and lift data. | Effect of sweep on hydrofoil performance and cavitation in water tunnel. |
| 34 | | ✓ | | ✓ | ✓ | | | ✓ | | Forces and moments on trailing wing in vortex wake. Forces and moments on vortex generating wing. | Outboard spoilers and trailing spline devices were effective in reducing trailing wing rolling moment in vortex wake up to 100 chordlengths downstream. |
| 35 | | ✓ | | ✓ | ✓ | | | ✓ | | Forces and moments on trailing wing and vortex generating wing. | Changes in span loading, spoilers, and splines are effective in reducing trailing vortex hazard. |
| 36 | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | Visual cavitation inception. Model propeller thrust and torque. | Cavitation and performance of bulbous tipped propeller results look encouraging. |
| 37 | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | | Visual cavitation inception for hydrofoil. | Concerns kinematics of motion of trailing wake of propeller and tip vortex dynamics. Solves numerically for wing and applies results to propeller theory. |
| 38 | | ✓ | | ✓ | ✓ | | | ✓ | | Wing suction air velocity, lift, profile drag, chordwise pressure distribution and boundary layer profiles on wing. | 2-D study of suction and roughness on wing performance. $C_L$ increase form 1.3 to 1.8 with suction. Roughness has no effect on $C_L$. |
| 39 | ✓ | ✓ | | ✓ | ✓ | | | | ✓ | Vortex wake tangential velocities measured from aircraft flybys. | Extends Betz method to case of flapped wing to calculate wake vortices. Computed velocities agree favorably with experiment. |
| 40 | | ✓ | | ✓ | ✓ | | | ✓ | | 5-hole pitot tube used to calculate radial, tangential, and axial velocities in vortex core. | Investigates viscous decay of steady 3-D helical vortex. Velocity distribution in good agreement with theory of Newman. |

## Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM | | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | AIR | WATER | | | | | |
| 41 | | ✓ | | ✓ | ✓ | | | ✓ | | Pitot tube wake survey in wind tunnel. | Comparison of tip vortex of 3 wing shapes with Betz theory. Good correlation except in vortex core. |
| 42 | | ✓ | Helicopter Rotor Blades | ✓ | ✓ | | | ✓ | | Stress measurements on rotor blades. Lift, drag, and moment via force balance. | Reverse-velocity rotor system was free from instability. Test results agree with predictions. |
| 43 | ✓ | | | Slender Body | ✓ | | | | | | Method for estimating the strength of wake vortices shed from slender body. Method applicable to wing vortices. |
| 44 | | ✓ | | ✓ | ✓ | | | ✓ | | Hot wire, visual. | Detail measurement of flow about (inside boundary layer of) wing tip. |
| 45 | ✓ | | | | | | | | | | Structure of turbulent line vortices is examined. Argues that vortex must develop overshoot of circulation to entrain fluid faster than molecular diffusion. |
| 46 | | ✓ | | Body of Revolution | ✓ | | | ✓ | | Flow visualization via vapor screen. | Study of behavior of vortices formed in separated region of an inclined body of revolution. Nose shape influences vortices. |
| 47 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Vortex structure downstream, lift, boundary layer characteristics via flow visualization. | Considers effect of wing geometry and pressure side boundary layer on trailing vortex. |
| 48 | ✓ | | | ✓ | ✓ | | | | | | Calculates vortex roll up behind wings at high $C_L$. Shows effect of ground and wind tunnel constraints on vortex. |
| 49 | ✓ | | | ✓ | ✓ | | | | | | Numerical method including self-induction for vortex wakes in the far field. |
| 50 | ✓ | | | ✓ | ✓ | | | | | | Semiempirical analysis of vortex formed from shear layer emanating from slender wing. |
| 51 | ✓ | | | ✓ | ✓ | | | | | | Predicts flow field within vortex core separating from leading edge of a slender delta wing. Predictions agree with experiment. |
| 52 | | ✓ | | ✓ | ✓ | | | ✓ | | | Shows numerically that vortex breakdown does occur with a pronounced deceleration of axial flow, at location where breakdown is observed. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 53 | ✓ | | | | | | | | | | Reexamines and clarifies the classical analysis of vortex sheet roll up by Rosenhead. Demonstrates that sheet rolls up in a more regular manner. |
| 54 | ✓ | | | ✓ | ✓ | | | | | | Assumes a continuous trailing vortex sheet rolls up into two discrete vortices. Estimates size and spacing of vortex cores. |
| 55 | | ✓ | | | ✓ | | | | | Flow visualization. Swirl angle distribution. | Studies vortex breakdown by observing vortices which are generated in a long cylindrical tube. |
| 56 | | ✓ | | ✓ | | ✓ | | ✓ | | Water tank flow visualization for vortex structure and longitudinal core velocity. | Examined vortex generated from foil tip. Center of vortex follows foil while outside purely rotational. Motions combine. |
| 57 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Visual and drag force. | Investigates performance of several tip shapes and modifications. |
| 58 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Vortex core velocities with pitot tube yaw probe. | Establishes laws governing the flow in turbulent line vortex. Shows that circulation is proportional to log of core radius. |
| 59 | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | Propeller thrust and torque, flow visualization, injection parameters, and cavitation inception. | Flap reduced cavitation and increased thrust considerably. Efficiency decreased somewhat. |
| 60 | ✓ | | Helicopter Rotor Blades | | | | | | | | Modified vortex model based on airfoil lifting line theory. Includes nonuniform flow through the rotorplane. |
| 61 | | ✓ | | ✓ | ✓ | | | ✓ | | Air injection flow rate, vorticity measurements, and flow visualization. | Demonstrated upstream-facing jet more effective than downstream jet in reducing vorticity. |
| 62 | ✓ | | | | | | | | | | Uses Betz theory to estimate the radial distribution of the tangential velocity in a rolled up vortex. |
| 63 | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | Visual vortex study. | Theory developed for roll up process and compared with experimental data. |
| 64 | | ✓ | | ✓ | ✓ | | | ✓ | | Smoke flow visualization. | Axial injection into the core of a vortex reduces concentrated vorticity, governed by injection momentum flux. |
| 65 | | ✓ | | ✓ | ✓ | | | ✓ | | Smoke trace and soap bubbles flow visualization. Turbulence levels in vortex measured with hot wire. | Unique facility in which wing moves through air and vortex is fixed. Wing acceleration seen as a limitation. |
| 66 | | ✓ | | ✓ | | ✓ | | ✓ | | Rolling moment measured on trailing model. | Wake measurements behind Boeing 747 model. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 67 | ✓ | | ✓ | | | | | | | | Derives relations between velocity field induced far behind the propeller and external forces representing the propeller. |
| 68 | | ✓ | | ✓ | ✓ | | | | ✓ | Vortex velocity via pitot tube on trailing plane. Flow visualization via smoke. | Measures velocity distribution of trailing vortices of full-scale airplane. |
| 69 | ✓ | | | ✓ | | | | | | | Iterative procedure for determination of vortex sheet location represented by discrete vortices, for given flow conditions. |
| 70 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Pitot tube rake and vorticity meter measured lift distribution, shape, and location of vortex sheet downstream. | Potential flow model of vortex wake gives good experimental representation of shape and velocity distribution of vortex wake. |
| 71 | ✓ | | | ✓ | ✓ | | | | | | Reviews fluid dynamic aspects of control of wingtip vortices. Derives vortex equation of motion and method for vortex control. |
| 72 | ✓ | ✓ | Helicopter Rotor Blades | | ✓ | | | ✓ | | Rotor thrust, torque, and rpm. Flow visualization via smoke rakes. | Evaluates accuracy of various analytical methods which predict rotor performance, compares with experimental data. |
| 73 | | ✓ | Helicopter Rotor Blades | | ✓ | | | ✓ | | Lift, drag, thrust, and torque for rotor. Flow visualization via smoke and Schlieren photographic technique. | Investigates effects of inter-blade spacing and pitch on rotor performance. The OGEE tip reduces the vortex concentration. |
| 74 | ✓ | | | ✓ | | | | | | | Study of vortex stability and possibility of purposely destabilizing them. Inviscid theory. |
| 75 | ✓ | | | ✓ | | | | | | | Study of vortex stability and possibility of purposely destabilizing them. Inviscous theory. |
| 76 | ✓ | | | | | | | | | | Behavior of vortex in viscoelastic fluid. |
| 77 | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | Velocity measurements in far-field wake. Vortex core observations via hydrogen bubbles. | Tip vortex decay rates at 100-1000 chord-lengths downstream. Results not applicable to large-scale aircraft vortices. |
| 78 | ✓ | | | ✓ | | | | | | | Explicit analytical perturbation solution based on Betz rollup theory for elliptic wings. |
| 79 | | ✓ | | ✓ | ✓ | | | ✓ | | Axial and tangential velocities within trailing edge vortex via 5-hole pitot tube. | Extends existing data to 10-26 chord lengths downstream. |
| 80 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Mapping of tip vortex core profile via 5-hole pitot tube. | A numerical solution of the tip vortex breakdown (burst) phenomenon is developed. Theory agrees with experiment. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM | | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | AIR | WATER | | | | | |
| 81 | ✓ | | | | | | | | | | Complete sets of time-dependent solutions for Stokes' slow-motion equations are constructed. They describe growth and decay of vortices. |
| 82 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Visual, hot-wire, and vorticity measurements of velocity decay in vortex core. | Calculates induced vortex core velocity and time decay. Good agreement with measurements. |
| 83 | | ✓ | | ✓ | ✓ | | | ✓ | | Tip vortex core velocities via 5-hole yawed pitot tube. | Wing tip modifications, such as spinning blades, obtain benefits similar to mass injection without the use of additional power. |
| 84 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Detailed flow (velocity) measurements in foil vortex using 5-hole pitot probe arrangement. | Mass injection (air) at wingtip destroys peak tangential *velocities in the vortex* core. |
| 85 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurement of vorticity, radius, velocity, and circulation in vortex core shed from aircraft wing. | Develops instrument to measure streamwise in wake of aircraft wing. Measurements agree with existing theory and data. |
| 86 | | ✓ | | ✓ | ✓ | | | ✓ | | Rotor blade six components of force and moments. Vorticity distribution in vortex wake. | Investigation of several devices to reduce vortex core tangential velocities. Porous tip found to be the most effective (factor of 10). |
| 87 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | Rotational velocity measured via vorticity meter in trailing vortex structure. | Considers wingtip droop on structure of its trailing vortex. Droop angle of 90 deg most effective. |
| 88 | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | | Cavitation *inception* for 20 *wings:* elliptic, rectangular, and delta. | Tip vortex cavitation dependent on boundary layer thickness on pressure side. Core thickness independent on induced drag Reynolds No. Scaling (linear). |
| 89 | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | Vortex vorticity and velocities with novel instruments in wind tunnel and full-scale plane. | Semiempirical model to predict vortex geometry and velocity field from wing far field/near field. |
| 90 | | ✓ | | ✓ | ✓ | | | | ✓ | Hot-film measurement of near-wing vorticity for various flight conditions. | Results present a series of contours of vorticity components. Data compared to 2-D inviscid theory. |
| 91 | ✓ | | | | ✓ | | | | | | Uses Green's function to calculate rollup of a vortex sheet. Shows differences between free-air and bound vortex sheet. |
| 92 | | ✓ | | ✓ | ✓ | | | ✓ | | Pressure taps on wing surface, lift and drag. | Effect of winglets on wing performance. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM: AIR | MEDIUM: WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 93 | ✓ | | | ✓ | | | | | | | Analytical study of laminar wing vortices. Found axial velocities can be toward or away from wingtip, dependent on loading. |
| 94 | ✓ | | | | | | | | | | Numerical study of a point vortex representation of the evolution of an initially plane vortex sheet. |
| 95 | ✓ | | | ✓ | | | | | | | A small perturbation analysis for a laminar vortex is given. Equations of motion are linearized. Fair agreement with measurements. |
| 96 | ✓ | | | ✓ | | | | | | | Assumes three stages for vortex pair decay and calculates examples. |
| 97 | ✓ | | | | | | | | | | Vortex disintegration is contributed to an instability mechanism rather than viscous decay. |
| 98 | | ✓ | | ✓ | ✓ | | | ✓ | | Axial and tangential velocity measurements via laser Doppler velocimeter. | Velocity measurements in wakefield include presence of pylons, nacelles, and wing flaps. |
| 99 | ✓ | | | ✓ | ✓ | | | | | | Calculates decay of a trailing vortex containing a turbulent core. Better agreement with experimental data than Squires theory. |
| 100 | ✓ | | | | | | | | | Flow visualization of trailing vortex structure. | Stability theory for wave-like disturbance in trailing vortices modified to account for finite core radii and distributions of vorticity. |
| 101 | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | Qualitative flow visualization of vortex structure. Trailing aircraft rolling moment. | Discusses experimental program to determine means to reduce lift-induced wingtip vortex intensity. |
| 102 | | ✓ | | ✓ | ✓ | | | | | Axial, tangential, and radial velocities measured via pitot tube and hot wire. | Injects air into vortex core to show circumferential velocity distribution is independent of axial flow of vortex in near field. |
| 103 | ✓ | | | ✓ | ✓ | | | | | | Develops mathematical models to represent devices that dissipate wingtip vortices in order to calculate their effects on wing performance. |
| 104 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurements of vortex structure behind 35 deg swept wing; wing loading via pressure distribution and induced rolling moment on trailing wing models. | Moment on trailing wing gives an easy single measurement to indicate the degree of shear layer rollup. |
| 105 | ✓ | | | ✓ | | | | | | | Numerical rollup method given for drooped and normal wingtips. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 106 | | ✓ | | ✓ | ✓ | | | ✓ | | Lift, drag, moment, injection parameters, tip vortex structure, and velocities via hot-wire and flow visualization. | Beneficial effects obtained from injecting air into trailing tip vortex core without adverse effects on wing performance. |
| 107 | | Proposal ✓ | | ✓ | | ✓ | ✓ | ✓ | | Measure lift, drag, acoustic signature, and flow visualization for four basic configurations. | Improve performance of various control surfaces with devices such as snags and strakes which alleviate stall. Apply to leading edge vortex. |
| 108 | | Proposal ✓ | ✓ | | | ✓ | ✓ | ✓ | | Propeller thrust and torque, mass injection rates, flow visualization, acoustic signature, and cavitation inception. | PROPOSAL--to demonstrate that liquid injection from propeller leading edge will reduce induced drag, alleviate tip vortex, and attenuate noise spectrum. |
| 109 | | ✓ | | ✓ | ✓ | | | ✓ | | Vortex core diameter, tangential and axial core velocities via triaxle hot wire. Spanwise lift distribution via pressure taps on wing surfaces. | Determines scaling parameters for flow in-core region of vortex. Peak tangential velocities generated by OGEE tip substantially less than parent tip. |
| 110 | ✓ | | | ✓ | ✓ | | | | | | Simplifies Betz rollup equations and extends them to make estimate of vortex structure behind wings with arbitrary spanwise load distributions. |
| 111 | ✓ | | | ✓ | | | | | | | It is found that substantial reductions in rolling moment are predicted for certain range of generating and following wing span ratios. |
| 112 | | ✓ | | ✓ | ✓ | | | ✓ | | Velocity and rolling moment on model wing in wind tunnel. | Study of effect of change in wingspan loading on wake velocities. |
| 113 | ✓ | | | ✓ | ✓ | | | | | | Introduces the inverse rollup method which predicts wing loading from given vortex structure. |
| 114 | ✓ | | | ✓ | ✓ | | | | | | Various ways in which vortical regions interact are developed by numerical analysis of inviscid time-dependent convective motions of the vorticity. |
| 115 | ✓ | | | ✓ | | | | | | | Theory given for Reynolds No. dependence on decay. Vortex taken as three parts. Axial velocities in core calculated. |
| 116 | ✓ | | | ✓ | | | | | | | Study of vortex rollup behind high aspect ratio wings. Infers vortex structure, decay, axial velocities, and instabilities. |
| 117 | ✓ | | | | | | | | | | 2-D potential theory solution for a free line vortex over a wing. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM AIR | MEDIUM WATER | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 118 | | ✓ | | ✓ | | ✓ | ✓ | ✓ | | Visual and acoustic cavitation inception in a water tunnel. | Experimental study of effect of surface roughness on cavitation. Examines region of cavitation. Some application to cavitation in lines vortices. |
| 119 | | ✓ | | ✓ | ✓ | | | | ✓ | Vortex vorticity measurement of aircraft flyby. Also some flow visualization. | Study of parameters affecting vortex decay rate. |
| 120 | | ✓ | | ✓ | ✓ | | | ✓ | | Flow visualization and measurement of wing forces and moments, also swirl velocity in core. | Mass injection most efficient for spanwise blowing. Injection normal to chord increased $C_L$ significantly. |
| 121 | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | Vorticity field in vortex core for near field and far field. Other vortex characteristics studied also. | Demonstrates use of holes (porosity) to reduce tangential velocities in trailing vortex core. 10 percent porosity shows 60 percent reduction in velocity. |
| 122 | | ✓ | | ✓ | ✓ | | | ✓ | | Rolling moment had velocity profiles measured in vortex core with and without air injection. | Studies suggests poorer results than previously thought for mass injection. |
| 123 | | ✓ | | ✓ | ✓ | | | ✓ | | Flow visualization via tufts and oil patterns, also measurement of foil forces and moments. | Effects of leading edge serrations on 2-D airfoil. Serrations created vortices which increased maximum lift of airfoil. |
| 124 | | ✓ | Helicopter Rotor Blades | | ✓ | | | ✓ | | Measurement of rotor thrust and torque. Also sound pressure levels in rotor near field. | Results of acoustic test of rotor with leading edge serrations show serrations more effective at speeds less than 135 m/sec. |
| 125 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurement of wing lift, drag, vortex core vorticity, and sound pressure levels. Also flow visualization. | Consider ten tip configurations to determine maximum velocity reduction in vortex core, 12 percent reduction maximum. |
| 126 | | ✓ | Helicopter Rotor Blades | ✓ | ✓ | | | ✓ | ✓ | Measurement of total lift, pressure on lifting surface, and sound pressure levels. Flow visualization via smoke and oil. | Studies to determine effects of blade tip profile and planform on performance. 2-D and 3-D models at low and transonic speeds. |
| 127 | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | Flow visualization via high-speed photography. | The motion of trailing vortices studied in both theory and experiment to determine vortex distribution for downwash calculations. |
| 128 | ✓ | | | ✓ | | | | | | | Considers growth of line vortex with time and the spread of a vortex behind a wing, due to turbulence. Eddy viscosity function of circulation. |
| 129 | ✓ | | | ✓ | | | | | | | Model for vortex core formed for slender delta wing. Solution in form of an asymptotic expansion. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM | | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | AIR | WATER | | | | | |
| 130 | | ✓ | | ✓ | | ✓ | | ✓ | | Flow visualization via hydrogen bubble, done in small towing tank. | Study of wingtip modifications on trailing vortex. Circulation endplate, perforated tip extension and tip spoiler on upper surface found to be most effective. |
| 131 | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | Flow visualization via hydrogen bubble, done in small towing tank. | Qualitative study of factors which control the axial flow field. Explains differing results of previous studies. |
| 132 | | ✓ | | ✓ | | ✓ | | ✓ | | Flow visualization via hydrogen bubble, done in small towing tank. | Qualitative study of factors which control the axial flow field. Explains differing results of previous studies. |
| 133 | ✓ | | | ✓ | | | | | | | Numerical solution of incompressible Navier-Stokes equations, applied to flow around rectangular slab. |
| 134 | ✓ | | | | | | | | | | Analytical study of the motion of a vortex in a 2-D incompressible nonuniform stream as solutions to the Navier-Stokes equations. |
| 135 | ✓ | | | ✓ | | | | | | | Discussion of Navier-Stokes solutions for vortex decay, including problems associated with inviscid theory. |
| 136 | | ✓ | | | ✓ | | | ✓ | | Measurement of direction, total head, and static pressure in pipe-generated vortex. Also flow visualization. | Study of vortex growth in turbulent pipe to aid in predicting real full-scale vortex growth. |
| 137 | ✓ | | ✓ | | | ✓ | | ✓ | | | Concerned with hub vortex. Documents design of free-vortex generator. |
| 138 | ✓ | | | ✓ | ✓ | | | | | | Application of a novel potential flow computational technique to solution of subsonic 3-D flow over wings with leading edge vortex separation. |
| 139 | ✓ | | | ✓ | ✓ | | | | ✓ | | An analysis, based on current understanding of vortex structure, to provide effect on aircraft encountering vortices, circumstances of occurrence. |
| 140 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurement of lift, drag, wing circulation via pressure taps for model in wind tunnel. | Effect of winglets on aircraft wing performance. |
| 141 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurement of wing forces, moments, and pressure distribution. Flow visualization and wake velocity measurements. | Improvement of performance for low-aspect-ratio swept wing with addition of snags and strakes. |

Table A1(Continued)

| BIBLIOG. NO. | THEORY | EXPERIMENT | PROPELLER | PLANAR LIFTING SURFACE | MEDIUM | | CAVITATION DATA | MODEL | FULL SCALE | TYPE OF MEASUREMENT | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | AIR | WATER | | | | | |
| 142 | | ✓ | Helicopter Rotor Blade | ✓ | ✓ | | | | ✓ | Measurement of blade thrust and torque, and vorticity distribution in trailing vortex. Flow visualization. | Mass injection rapidly dissipates the circulation energy of tip vortex. Defines efficient injection system parameters. |
| 143 | ✓ | | Helicopter Rotor Blade | | ✓ | | | | ✓ | | Summary of devices to eliminate tip vortex for helicopter rotors. Mass injection system seen as best solution. |
| 144 | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | Generated vortex pair in water channel and measured amplification rate of vortex instability using flow visualization and hot-wire probe. | Method of matched asymptotic expansions used to obtain general solution of flow field within and near the vortex. |
| 145 | ✓ | | | ✓ | ✓ | | | | | | Models trailing vortex wake with laminar, viscous vortex models. Treats near-, intermediate-, and far-field wake. Model agrees with experiment. |
| 146 | ✓ | | | ✓ | ✓ | | | | | | Calculates initial inplane acceleration of a vortex in 2-D incompressible flow, in the immediate vicinity of an aircraft. |
| 147 | | ✓ | | ✓ | ✓ | | | ✓ | | Measurement of wing forces and downstream velocity distribution via triple-sensor hot-film probe. | Vortex abatement device reduces size and strength of wingtip vortex; also increases lift and decreases drag. |
| 148 | | ✓ | | ✓ | ✓ | | | ✓ | | 3-D hot-wire (velocity) anemometer for three wingtip configurations in wind tunnel. | Shows effect of axial mass injection on core velocity and turbulence. |

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